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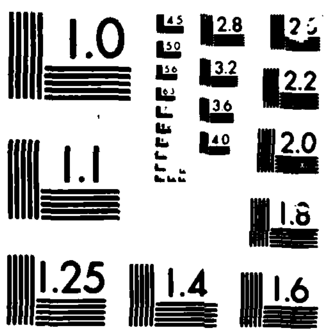

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NRL Memorandum Report 5773

An Investigation of Stress-Corrosion Cracking Susceptibility in Candidate Steels for Tension Leg Platform Tendons

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Material Science and Technology Division

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Consideration of the use of high-strength steels in tension leg platform (TLP) tendons raises questions concerning the possibility of stress-corrosion cracking (SCC) occurring over long periods of time. For this reason, an investigation was undertaken to experimentally characterize the SCC susceptibility of eleven candidate materials using state-of-the-art fracture mechanics methodology. The materials studied in this program were provided by Conoco, Inc. and Chevron Corporation from samples being characterized to TLP service. The materials included steels in various product forms including forgings, rolled plate and weldments with yield strengths ranging from 80 to 125 ksi. The SCC tests were conducted at the NRL Marine Corrosion Research Laboratory in Key West, Florida. Bolt-loaded wedge-opening-loaded (WOL) precracked specimens were exposed to fresh flowing natural seawater while cathodically coupled to zinc anodes for a minimum of 8,000 hours (333 days). No evidence of SCC susceptibility was found in any of the materials tested. A limited number of additional experiments were conducted to further confirm this favorable finding. Based on the results of this exploratory study, static-load SCC does not appear to pose a threat to the structural integrity of high-strength steel TLP tendons currently being considered for offshore application in U.S. coastal waters.

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CONTENTS

AN INVESTIGATION OF STRESS-CORROSION CRACKING SUSCEPTIBILITY IN CANDIDATE STEELS FOR TENSION LEG PLATFORM TENDONS

INTRODUCTION

The use of high-strength steels in tendons for tension leg platforms (TLP's) raises questions concerning the possibility of stress-corrosion cracking (SCC) occurring over long periods of time [1-3]. SCC is a type of spontaneous cracking which can develop slowly in many high-strength steels in seawater under the combined action of sustained tensile stress, which TLP tendons will experience, and exposure to a corrosive environment, which TLP tendons may suffer if corrosion protection systems deteriorate in service. If allowed to progress unchecked, SCC can potentially lead to catastrophic failure of a tendon.

Many lower-strength structural steels are considered to be immune to SCC in seawater at ambient temperatures, and thus the phenomenon is safely ignored for most conventional offshore structural applications which utilize steels in the 36 to 60 ksi yield strength range. However, research over the past two decades has demonstrated that sensitivity to SCC in seawater can be strongly dependent upon several controlling factors including yield strength, product form, and cathodic protection parameters. Sensitivity to SCC increases with increasing yield strength and increasing cathodic polarization, and weld metals tend to be more sensitive to SCC than wrought metals. Previous studies have shown that SCC in seawater can occur in wrought steels at yield strengths as low as 100 ksi [4,5] and in weld metals at yield strengths as low as 80 ksi [6]. Also, cathodic protection achieved by using potentials of approximately -0.8 to -1.0 V (versus Ag/AgCl) can significantly increase the susceptibility of high-strength steels to SCC [7,8]. Thus, based upon past research conducted on metallurgically similar steels for military applications, it was considered prudent to examine the SCC sensitivity of candidate steels for TLP tendon applications. Primarily because of the tensile loading involved, TLP tendon materials appear destined to enter service without the benefit of prior experience in similar applications.

MATERIALS

This investigation was conducted in two phases. In the initial phase, SCC tests were conducted on two samples of 3Ni-Cr-Mo-V steel provided by Conoco Inc. from separate producers. In the second phase, similar SCC tests were conducted on nine low-alloy steels provided by Chevron Corporation.

Chemical compositions and mechanical properties of all the materials studied in this program are provided in Tables 1 through 5.

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It is important to note that the steels provided by the two donors are intended for distinctly different tendon design concepts. The Conoco samples are from thick-section forgings of the type used for the monolithic tendons on the Hutton platform in the North Sea [9]. These materials were tested in the form of 2-inch-thick fracture mechanics specimens. In contrast, the Chevron materials were being characterized for a different tendon design concept involving thin-section tubular members welded to thick-section forgings at each end. These materials were tested in the form of 1-inch-thick fracture mechanics specimens.

EXPERIMENTAL PROCEDURES

The SCC studies employed in this investigation consisted of fracture mechanics tests using precracked specimens following established procedures [2,10]. The purposes of these tests were twofold: (i) to determine if SCC crack growth could be initiated in any of these TLP candidate materials, and (ii) if SCC crack growth did initiate, to measure the fracture mechanics threshold parameter, K_{Iscc}, below which SCC would not occur. As discussed in a previous report [3], the use of a threshold approach to achieve SCC prevention is the preferred method of assuring long-term structural integrity in TLP tendons.

With one exception, which will be cited separately, all tests in this investigation were performed using fresh flowing natural seawater at NRL's Marine Corrosion Research Laboratory located in Key West, Florida.

The test specimens used for the Conoco materials were 2-inch thick constant-displacement wedge-opening-loading (WOL) type, with overall dimensions conforming to the 2T configuration, Figure 1. The test specimens for the 1-inch thick Chevron materials were 1T WOL type, Figure 2.

In both cases, duplicate specimens of each materials were tested. For SCC testing of high-strength steels, an approximate one-year duration is recommended. For the Conoco materials, the duration of testing was 8,800 hours (368 days). For the Chevron materials, one specimen of each material was tested for 8,000 hours (333 days) and the second specimen was tested for 14,400 hours (600 days).

In both cases, test specimens were machined from blanks provided to NRL. Finished specimens were precracked by NRL to a crack length-to-width (a/W) of approximately 0.50 in ambient laboratory air using a maximum crack-tip stress-intensity factor of 40 ksi$\sqrt{in}$.

All test specimens were bolt-loaded at the Key West field site while the crack-tip region of each specimen was exposed to seawater. Internally strain-gaged bolts were used to monitor long-term changes in load. Initial K_I values ranged from approximately 95 to 110 ksi$\sqrt{in}$. Initial K_I values were determined from crack-mouth-opening-displacement data obtained from clip-gages applied to each specimen during loading. This is considered to be a more accurate method of measuring initial K_I values than using load data obtained from the strain-gaged bolts.

For long-term test purposes, the specimens were placed in polyethylene reservoirs through which the natural seawater flowed in a single-pass mode. In the reservoirs, two zinc anodes were connected to each specimen, one on each side of the crack. The zinc anodes provided a cathodic potential of approximately -1.03 V, versus a Ag/AgCl reference electrode, to simulate the

effects of cathodic protection. By the termination of testing, the potential had typically dropped to approximately -0.99 V. Zinc anodes, rather than an impressed current potentiostat, were chosen for long-term test purposes because the Key West field site is subject to power outages which could disrupt an impressed-current system. The temperature of the seawater was uncontrolled and varied between extremes of approximately 60 to 80°F, with a year-round average temperature in excess of 70°F. The use of fresh flowing seawater assured that the test solution was fully oxygenated at all times.

Strain-gage readings from the loading bolts were taken daily to monitor any long-term load changes. Load reductions over time are indicative of either stress relaxation or SCC crack growth. Upon completion of exposure testing at Key West, the specimens were returned to NRL, unloaded and subsequently broken open to reveal the fracture surfaces for visual evidence of SCC crack growth. A representative photograph of a specimen fracture surface is shown in Figure 3.

RESULTS AND DISCUSSION

None of the test specimens in this investigation showed evidence of SCC. In several instances, strain-gaged bolt readings indicated gradual load reductions over periods of several months. However, post-test examinations of fracture surfaces failed to reveal evidence of crack growth. Looking at a typical fracture surface photograph, shown in Figure 3, several distinct areas can be seen: (1) machined notch, (2) fatigue precrack, and (3) post-test mechanical overload fracture. If SCC had occurred, there would be visible evidence of a distinctly different area of crack growth between the fatigue precrack and the post-test fracture areas. This is because in steels of this type, fatigue, SCC and mechanical fracture each produce distinct fracture surface morphologies, which can be differentiated by visual examination. No SCC was evident on the post-test fracture surfaces of any of the specimens tested. Thus, the recorded load reductions were attributed to stress relaxation of the specimen or to failure of the strain gage.

The results of these tests are favorable for the use of these candidate steels in TLP tendon construction. However, one caveat should be added at this point. This investigation was conducted in parallel with a Navy program on standardization of fracture mechanics SCC test methods. The constant-displacement WOL specimen was chosen for this study because of its convenience as compared with alternate fracture mechanics test methods. The WOL test has enjoyed broad usage for many years, and can provide both a qualitative go/no-go answer plus a quantitative measure of K_{Iscc} with a single specimen test. Alternate methods of fracture mechanics SCC testing require more specimens, and often add both time and expense.

However, in the course of the parallel Navy program on test method standardization, it was discovered that the constant-displacement WOL test can sometimes fail to reveal potential SCC susceptibility in ductile high-toughness steels, such as those studied in this investigation [11]. The suspected reason for this apparent failure of the WOL test is mechanical spring-back of the specimen in ductile steels where a large plastic zone has formed at the tip of the crack. Such spring-back, when it occurs, tends to reduce the actual loading at the crack tip where SCC must initiate if it is to occur.

For this reason, a sample of Conoco steel B was machined into a 2 x 2 inch cantilever-bend specimen for subsequent testing at NRL in Washington. The test environment was 3.5 percent aqueous NaCl solution and an impressed-current potentiostat device was used to provide a cathodic potential of -1.0 V. Experience with the Navy test method development program suggested that this combination of experimental variables was potentially somewhat more severe than those used in the original testing at Key West [12]. Unfortunately, this recent insight into SCC test methods was developed too late to be used to advantage in this program. The cantilever specimen was loaded to a K_I value of 100 ksi√in. for 2,000 hours without evidence of crack growth, and then was step-loaded to a K_I level of 120 ksi√in. for an additional 3,500 hours without evidence of crack growth. This steel was chosen for additional testing because the two Conoco steels were significantly higher in yield strength than any of the Chevron steels, and thus were potentially more susceptible to SCC. This negative result under these very severe conditions suggests that, by any measure within the authors' experience, this is a very SCC-resistant high-strength steel. Therefore, the authors feel that is is unlikely that any of the steels studied in this program are susceptible to static-load SCC.

CONCLUSION

Each of the steels studied in this investigation showed no evidence of susceptibility to seawater stress-corrosion cracking (SCC) using conventional fracture mechanics test procedures and simulated cathodic protection involving zinc anodes. These results suggest that SCC under purely static loading is not likely to be a significant factor in structural applications for these steels involving marine environments and cathodic protection. Further studies are underway to investigate the potentially deleterious effects of small-amplitude cyclic loading on SCC in high-strength steels for marine applications.

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TABLE 1 - Chemical Compositions of Steels Provided by Conoco Inc.

Material	Element (weight percent)											
	C	Si	Mn	P	S	Ni	Cr	Mo	V	N	Sn	Cu
Conoco B	0.29 max	0.05 max	0.39 max	0.008 max	0.004 max	3.54-3.61	1.46-1.52	0.48-0.54	0.13 max	0.004 max	0.007 max	-
Conoco J	0.27 max	0.06 max	0.24 max	0.006 max	0.002 max	3.66-3.84	1.79-1.85	0.39-0.42	0.13 max	0.004 max	0.006 max	-

TABLE 2 - Tensile Properties of Conoco Steels

Material	0.2% yield strength (ksi)	Ultimate tensile strength (ksi)	Reduction in area (%)	Elongation (%)
Conoco B	121	139	67	23
Conoco J	125	141	72	24

TABLE 3 - Identification of Steels Provided by Chevron Corporation

Sample I.D.	Material	Condition
A	2-1/4Cr-1Mo,JSW	Quenched & Tempered (Q&T)
C	U-80 plate, Summitomo	Quenched & Tempered (Q&T)
D	U-80 longseam weldmetal, Summitomo	Quenched & Tempered (Q&T)
E	U-80 plate, NKK	Quenched & Tempered (Q&T)
F	U-80 longseam weldment, NKK	Quenched & Tempered (Q&T)
G	U-80 plate, Kawasaki	Quenched & Tempered (Q&T)
H	U-80 longseam weldmetal, Kawasaki	Quenched & Tempered (Q&T)
I	Weldmetal, NKK U-80 to JSW 2-1/4Cr-1Mo	Post Weld Heat Treated (PWHT)
J	Weldmetal, Kawawasaki U-80 to Kawasaki 2-1/4Cr-1Mo	Post Weld Heat Treated (PWHT)

TABLE 4 - Chemistry and Mechanical Properties of Chevron Steels

Sample	Chemistry									Heat Treatment		Mechanical Properties			
	C	Mn	Si	P	S	Ni	Cr	Mo	Other	Austenitize	Temper	Yield (ksi)	UTS (ksi)	El (%)	CVN ft-lbs,-5°F
A	.13	0.53	0.06	.007	.013	0.17	2.42	0.99	--	1706°F 5hr., WQ	1160°F 5hr.,AC	92.3	119.0	20	--
C	.12	1.24	0.31	.008	.001	0.86	0.29	0.20	--	1710°F 1/2hr.,WQ	1150°F 1 hr.	101	115	23	--
D										1710°F 1/2hr.,WQ	1150°F 1 hr.	--	99.9	--	--
E	.12	1.46	0.25	.018	.002	0.13	0.07	0.11	0.045V	1680°F WQ	1264°F 20 min.	89	99	26	230
F	.11	1.22	0.18	.017	.004	1.73	0.34	0.07	--	1680°F WQ	1264°F 20 min.	88	98	25	126
G	.10	0.83	0.26	.007	.001	1.18	0.50	0.45	--	N/A WQ	1256°F 1 hr.	87.8	101.3	27	215
H	.05	1.27	--	--	--	2.22	0.66	0.40	--	N/A WQ	1256°F 1 hr.	81	100	29	125
I	.12	--	--	--	--	0.6	0.8	0.6	--	None	1150°F 5hr.,AC	90.1	96.0	27	100
J	--	--	--	--	--	1.2	1.5	0.7	--	None	1200°F 1 hr.	88	102.5	27	90

TABLE 5 - Welding Parameters of Chevron Steels

Sample	Welding Process	Joint Design	Filler Metal		Preheat (min.)	Interpass (max.)	Heat Input
D	SAW	Double Bevel	Not Available (N/A)		N/A	N/A	N/A
F	DSAW	Double Bevel	Kobe US052 (0.9Mn-0.3Ni-1.0Cr) Kobe US72 (1.5Mn-0.5Mo-0.03V)		N/A	N/A	60 KJ/in
H	SAW	Double Bevel	1.0 Ni 0.5 Cr 0.4 Mo	3/16"ϕ	250°F	350°F	45 KJ/in
I	SMAW-Root SAW-Fill	Double Bevel	E8018-C1 EF1	5/31"ϕ 3/32"ϕ	350°F 350°F	700°F 700°F	34 KJ/in 36 KJ/in
J	SAW	Double Bevel	2.0 Ni 0.5 Cr 0.4 Mo	3/16"ϕ	300°F	400°F	100 KJ/in

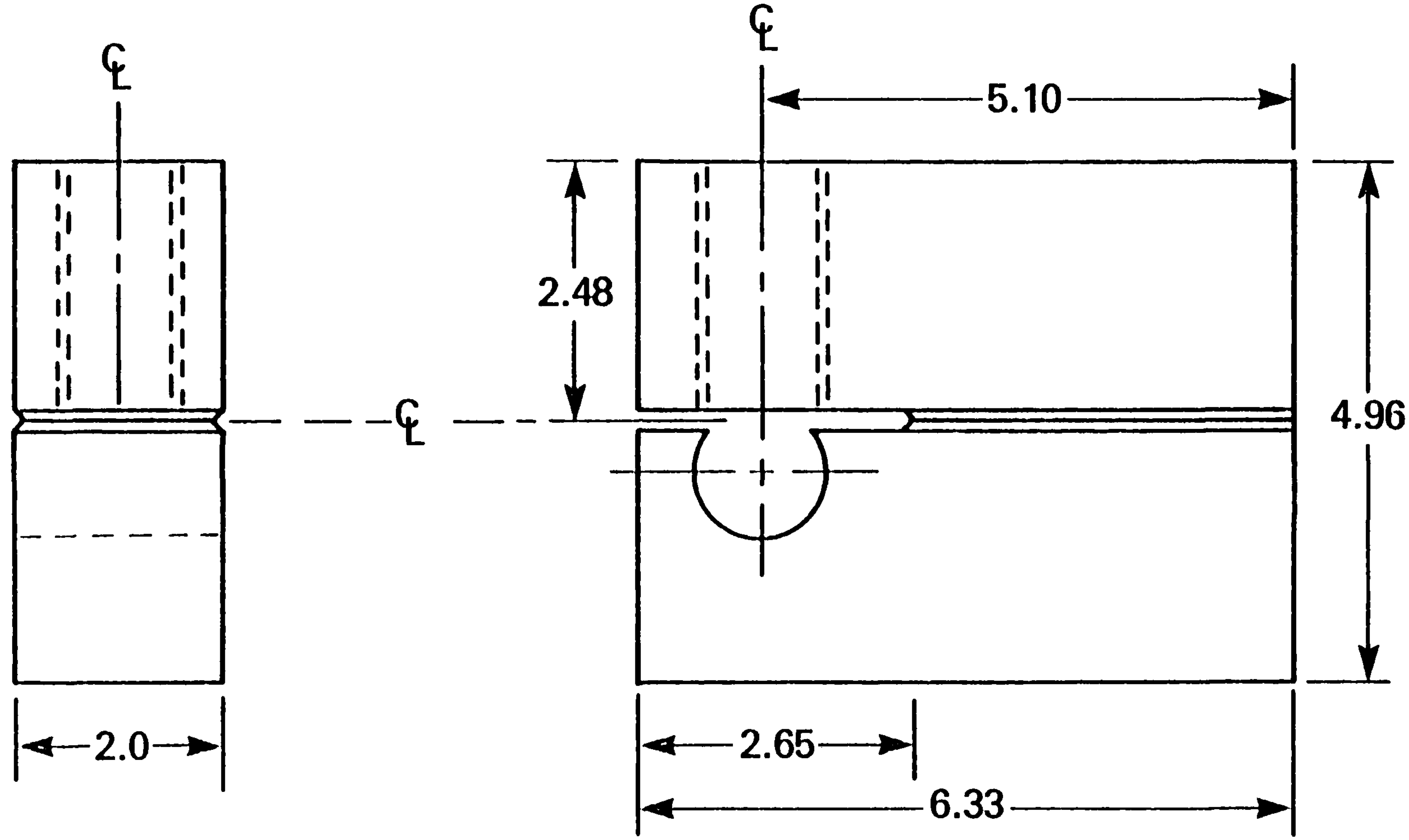

Figure 1 - Configuration and dimensions of the 2T bolt-loaded wedge-opening-loaded (WOL) fracture mechanics specimen used for stress-corrosion cracking tests. Dimensions are in inches.

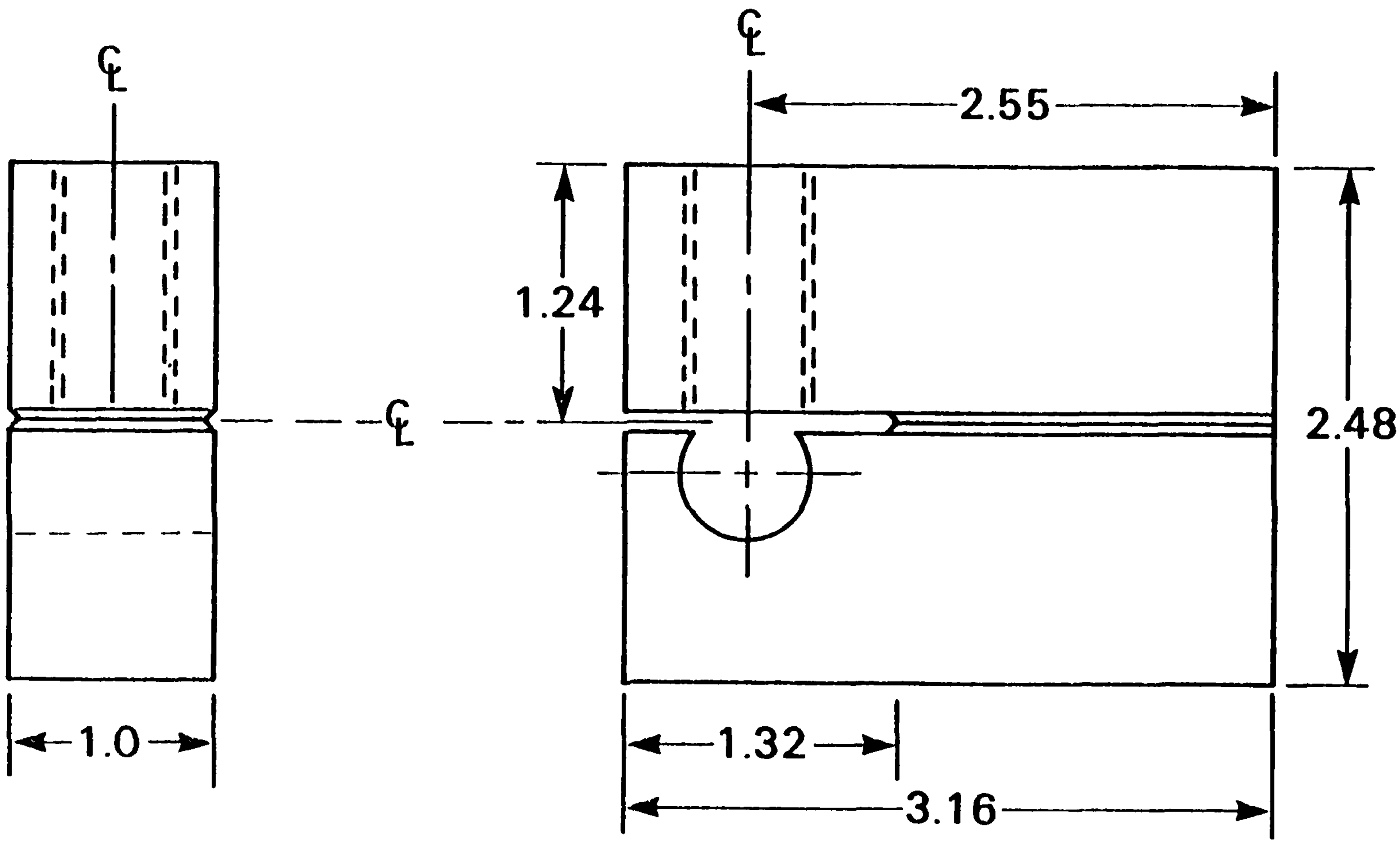

Figure 2 - Configuration of the lT WOL fracture mechanics test specimen.

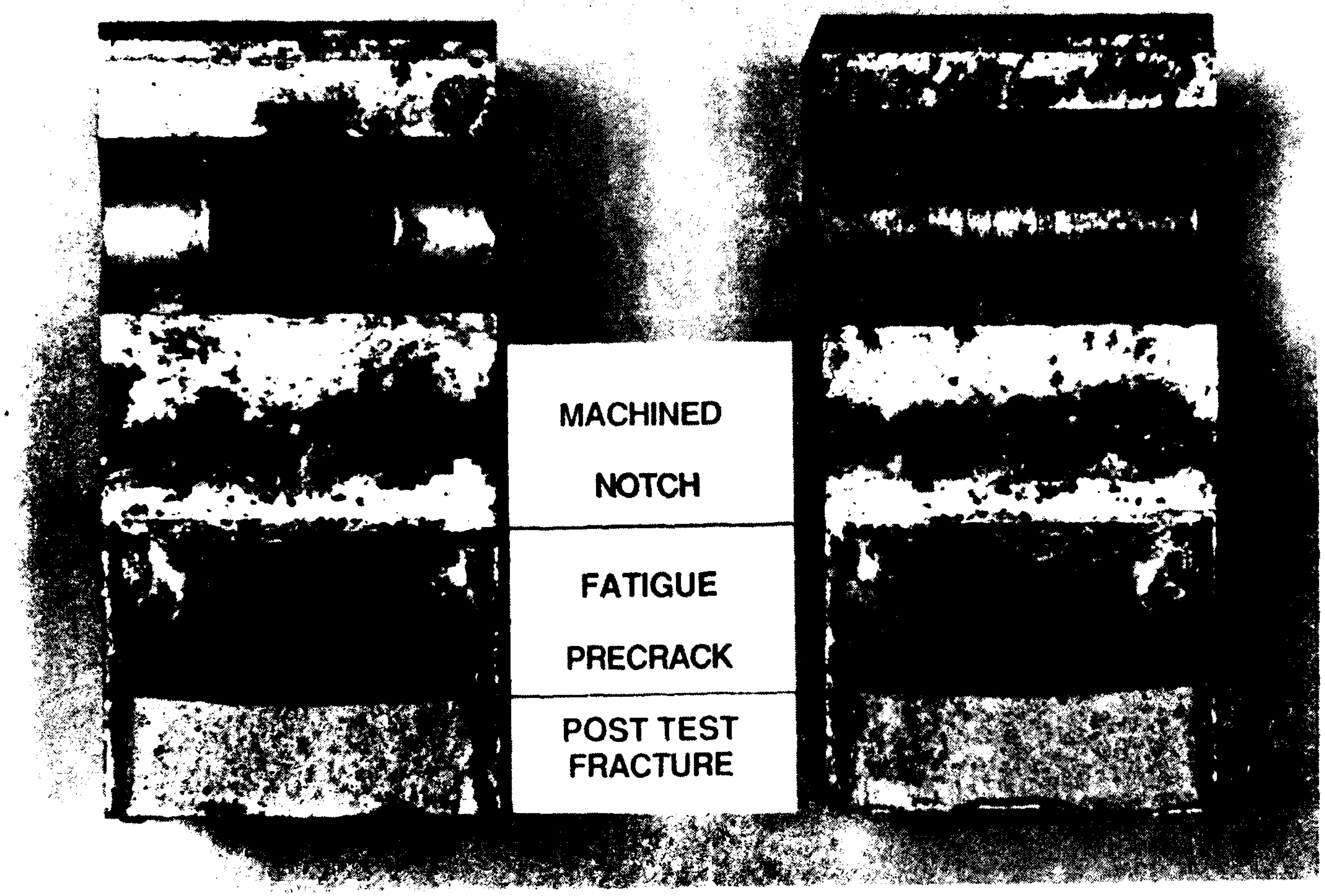

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Figure 3 - Post-test fracture surface of a WOL specimen tested in this investigation. Note the absence of any region of stress-corrosion crack growth between the corroded fatigue precrack area and the overload fracture surface created by breaking the specimen open after testing in seawater.

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